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SIRE: A MIMO radar for landmine/IED detection

Ode Ojowu Jr.[a], Yue Wu.[a], Jian Li*[a] and Lam Nguyen[b]

[a]Dept. of Electrical Engineering, Univ. of Florida, Address, Gainesville, FL., USA 32611-6130;
[b]U.S. Army Research Laboratory, Adelphi, MD 20783 USA

ABSTRACT

Multiple-input multiple-output (MIMO) radar systems have been shown to have significant performance improvements over their single-input multiple-output (SIMO) counterparts. For transmit and receive elements that are collocated, the waveform diversity afforded by this radar is exploited for performance improvements. These improvements include but are not limited to improved target detection, improved parameter identifiability and better resolvability. In this paper, we present the Synchronous Impulse Reconstruction Radar (SIRE) Ultra-wideband (UWB) radar designed by the Army Research Lab (ARL) for landmine and improvised explosive device (IED) detection as a 2 by 16 MIMO radar (with collocated antennas). Its improvement over its SIMO counterpart in terms of beampattern/cross range resolution are discussed and demonstrated using simulated data herein. The limitations of this radar for Radio Frequency Interference (RFI) suppression are also discussed in this paper. A relaxation method (RELAX) combined with averaging of multiple realizations of the measured data is presented for RFI suppression; results show no noticeable target signature distortion after suppression. In this paper, the back-projection (delay and sum) data independent method is used for generating SAR images. A side-lobe minimization technique called recursive side-lobe minimization (RSM) is also discussed for reducing side-lobes in this data independent approach. We introduce a data-dependent sparsity based spectral estimation technique called Sparse Learning via Iterative Minimization (SLIM) as well as a data-dependent CLEAN approach for generating SAR images for the SIRE radar. These data-adaptive techniques show improvement in side-lobe reduction and resolution for simulated data for the SIRE radar.

Keywords: Synchronous impulse reconstruction (SIRE), MIMO Radar, UWB, RFI Suppression, SAR

1. INTRODUCTION

The landmine crisis, which is a global problem, continues to affect both civilians and military personnel in conflict zones even long after said conflict has ended.[1] Detection and removal of landmines is an important task globally, and efficient as well as cost effective methods for detection are very important.

Low frequency ultra-wideband (UWB) radar has garnered attention for the detection of landmines in recent years.[2] The low frequencies used by these radars provide the necessary ground penetration capabilities for detection and the wide bandwidth signals used are necessary for range resolution. Cross range resolution which depends on the size of the antenna aperture can be improved by generating a synthetic aperture.[3] Typical airborne synthetic aperture radars (SAR) which can provide high resolution in cross range are not practical for this problem due to cost limitations.

Multiple-input multiple-output (MIMO) radars can also be used to create a virtual array aperture larger than their single-input single-output (SIMO) counterparts which allows for improved cross range resolution.[4–6]

Further author information: (Send correspondence to Prof. Jian Li)
Prof. Jian Li: E-mail: li@dsp.ufl.edu, Telephone: +1(352)392-2642

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MIMO radars operate by using multiple antennas to transmit waveforms which could be linearly independent and also uses multiple antennas (receivers) to receive the reflected signals from targets in a given scene.[3,7–9]

A MIMO radar with collocated antennas, can provide advantages over its SIMO counterpart by exploiting waveform diversity.[4–7,10,11] Some of the advantages afforded by this radar include an improved parameter identifiability (i.e., maximum number of targets that can be uniquely identified)[4,11] and improved cross range resolution.[4,6] This improved resolution can help resolve desired targets such as landmines from clutter.

In this paper, we present the Synchronous Impulse Reconstruction (SIRE) ultra-wideband (UWB) radar designed by the Army Research Laboratory (ARL)[12] as a 2×16 (2 transmitters, 16 receivers) MIMO radar, with collocated antennas. This radar which operates in forward looking mode and built for landmine and improvised explosive device (IED) detection is described herein. By transmitting orthogonal waveforms, improved cross range resolution compared to using a single transmitter can be observed, showing this radar to be a working example of a MIMO radar. This radar employs cost effective analog to digital (A/D) converters to sample its large signal bandwidth using an equivalent sampling scheme, making it practical for actual ground missions.[12]

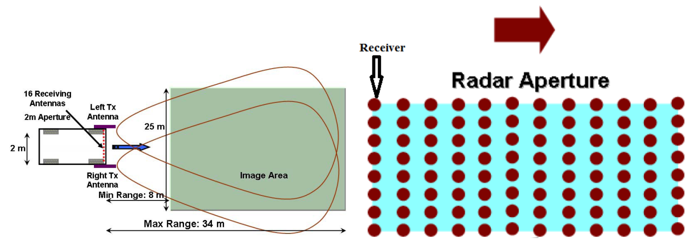
In Section 2, a brief overview of the SIRE radar is presented, including the equivalent sampling scheme used by this radar. In Section 3, this radar is described in a MIMO paradigm. The improved cross range resolution over its SIMO counterpart is also discussed, showing this radar as a practical working example of a MIMO radar. Imaging techniques both data-independent and data-dependent approaches are also discussed for this radar in this Section. In Section 4, Radio Frequency Interference (RFI) suppression (which poses a challenge due to the radar's equivalent sampling technique) is discussed. A method of suppression based on the relaxation algorithm - RELAX[13] is presented and discussed for this radar. Section 5 presents the conclusions of the paper.

2. THE SIRE RADAR

2.1 Overview

The SIRE radar is a low frequency, impulse based UWB radar developed by ARL.[12,14] The radar operates in forward looking mode with the goal of detecting landmines, IEDs and other concealed targets. The use of low frequencies in UWB radar is necessary for foliage/ground penetration, where as the use of UWB pulses are necessary for good resolution.[15] Downrange resolution of this radar is determined by the bandwidth of the transmitted pulse which occupies a frequency range of 0.3 to 3 GHz.[12] The cross range resolution will be determined by the physical aperture of this radar. The conventional method for imaging is performed using the standard back-projection/delay-and-sum (DAS) algorithm in forward looking mode.[12]

The SIRE radar system has a physical aperture (2m) consisting of 16 receive antennas,[14] timing and control cards are also present to provide the necessary clock references for the radar. Each antenna consists of a digitizer that integrates the radar returns from a number of pulses which it passes to the systems personal computer (PC) which acts as the operator control and display.[12,14] The radar consists of two transmitters at the ends of the receive array. The radar is mounted on truck and the radar imaging geometry as well as the data collection 2D aperture in forward looking mode are shown in Fig. 1.[12] The returned radar signals collected from this 2D aperture can be used for imaging the scene. The images are formed 8m (standoff range) ahead of the truck on which the radar is mounted.



(a) (b)

Figure 1. SIRE Radar - Forward Looking mode:[12] (a) Imaging Geometry (b) Radar Aperture

Due to the large bandwidth of the returned radar signals, conventional sampling will require high rate analog-to-digital (A/D) converters to digitize the returned radar signals. These high speed A/D converters are expensive to build and makes practical implementation improbable.[12] It is ARL's goal to develop a radar capable of landmine detection which is affordable and also in a lightweight package for practical applications.[12] Therefore, each of the receivers consists of a low-rate (40 MHz), commercially available (and inexpensive) A/D converter. The digitizers are used to sample the large bandwidth ($\approx$ 3GHz) of the returned signals using an equivalent sampling scheme termed the synchronous impulse reconstruction (SIRE) sampling scheme.[12,16]

2.2 SIRE equivalent sampling scheme

The SIRE sampling scheme involves sampling the returned radar signals from a scene at a significantly lower sampling rate $f_s = 40$ MHz, (with corresponding sampling period Δ_s), than the Nyquist rate, which leads to aliased samples. $N = 7$ aliased samples are collected per pulse repetition interval (PRI) or fast time, and for each subsequent PRI, N more samples are collected with the range profile shifted by Δ_e (in time). After $K = 193$ pulse repetition intervals (PRIs) or slow time, a total of $K \times N$ aliased samples are collected.[12,16] These samples are interleaved as shown in Fig. 2, which gives an effective sampling rate of $f_e = 1/\Delta_e = 7.72$ GHz that is above the Nyquist rate. Because the scene of interest is not changing with time, the returned samples from a given range bin theoretically should also remain unchanged in time. Therefore, the interleaved samples are effectively sampled above the Nyquist rate and are 'unaliased'.[12]

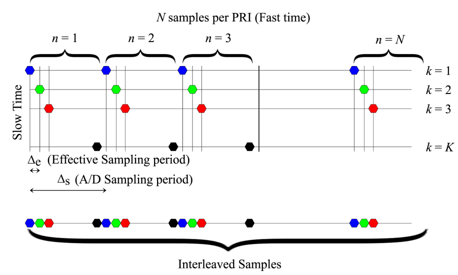


Figure 2. Synchronous Impulse Reconstruction equivalent time sampling

The measurements from each range profile are typically repeated M times and added coherently to improve the signal-to-noise ratio (SNR).[12] Fig. 2 shows the special case of $M = 1$.

As previously mentioned, the down-range resolution is determined by the bandwidth of the transmitted impulse. The cross range resolution, however, is limited by the 2m receive aperture of the radar. This cross range resolution can be improved by creating a virtual aperture larger than the physical aperture.

3. SIRE RADAR IMAGING: MIMO AND SIMO

The SIRE radar can be described as a practical example of a MIMO radar which exploits waveform diversity by transmitting orthogonal waveforms from the two transmit antennas located at the edges of the receive array. These orthogonal waveforms are achieved by alternatively transmitting echo pulses (in "ping-pong" mode) from each transmitter. This creates a virtual aperture which is effectively longer than the physical aperture of the radar.[17] Fig. 3 shows the virtual array created by this MIMO radar.

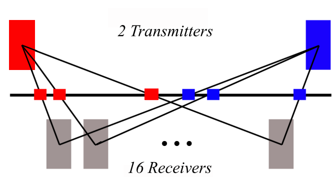


Figure 3. MIMO configuration

In this Section, we will review the standard data-independent method for image formation using the back-projection/delay-and-sum (DAS) algorithm and also the recursive side-lobe minimization (RSM) algorithm (for side-lobe reduction) for image formation developed by ARL.[12,18] Images will be formed using simulated data from a 2D aperture (radar moving forward) in "ping-pong" mode (MIMO mode)[19] and compared to the data using only a single transmit antenna (SIMO mode) to show the improved cross range resolution.

Data-independent methods of imaging are typically known to yield relatively poor resolution. In this Section also, we will present two data-adaptive methods which improve on the resolution over data-dependent methods. A sparsity based method known as sparse learning via iterative minimization (SLIM)[20] is presented as well as the CLEAN method.[21] These two methods require prior knowledge of the transmitted waveform, which can be estimated from the received measurements; they offer superior resolution over the data-independent methods.

3.1 Back-projection/DAS Algorithm

For a specific target (or pixel location) $i \in \{1, 2, \cdots, I\}$, the back-projection pixel value is given simply by:

$$B(i) = \sum_{k=1}^{K} w_{k,i} r_k(\hat{\tau}_{k,i}) \tag{1}$$

where $\{r_k(t)\}_{t=0}^{T-1}$ is the received measurements at the kth receiver, $\hat{\tau}_{k,i}$ is the delay estimate from transmitter to target to receiver, and $w_{k,i}$ is a weighting factor (compensating for attenuation). The envelope of this image can be computed using the Hilbert transform to provide a smoother image.[12]

This well known data independent method of image formation is limited due to poor resolution and high side-lobes. The recursive side-lobe minimization (RSM)[12,18] is an algorithm proposed by ARL for side-lobe reduction and is described next.

3.2 Recursive side-lobe minimization (RSM) Algorithm

The RSM algorithm[12,18] is based on the DAS algorithm and was proposed for side-lobe reduction. Consider a 2-D aperture with K receive elements, the RSM algorithm can be described as follows:

- Step 1: Generate L random compressive apertures with $M = \rho K$ elements where $0 < \rho < 1$.
- Step 2: Generate a DAS image envelope for each aperture $\{B_l(i)\}_{i=1}^{I}$ where $l \in \{1, 2, \cdots, L\}$.
- Step 3: Select the minimum value at each pixel location to form the final image.

The basic idea behind this algorithm is that, randomly selecting a smaller sets of data points will induce more side-lobes in the image domain which vary across images, whereas the target signatures remain consistent. Selecting the minimum values across images will effectively suppress side-lobes, leaving targets unaltered.[12,18]

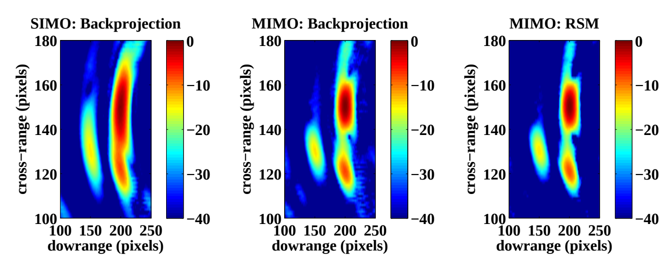


Figure 4. MIMO vs SIMO: Back-projection/DAS

Fig. 4 shows the back-projection image formed using received data from a single transmit antenna (SIMO case) compared to the MIMO case. An RSM image formed using the MIMO configuration is also shown. The MIMO radar can be seen to provide improved cross range resolution in both images showing the effectiveness of the SIRE radar as a MIMO radar.

The RSM algorithm provides side-lobe reduction compared to the standard DAS algorithm, without a change in resolution. We therefore investigate data-adaptive methods for improved resolution as well as side-lobe reduction.

3.3 Sparse Learning via Iterative Minimization (SLIM)

A sparsity promoting algorithm known as sparse learning via iterative minimization (SLIM) was originally presented for high resolution MIMO radar imaging.[20] This algorithm is based on a *maximum a posterior* (MAP) method with a hierarchical model and uses a sparsity promoting prior. This data-adaptive algorithm has been shown to outperform other sparsity based algorithms such as CoSaMP and can provide accurate estimates even when the sources are coherent.[20] This algorithm is proposed here for imaging to provide improved resolution over data-independent methods based on the following simple linear model.

$$\mathbf{y} = \mathbf{A}\boldsymbol{\beta} + \mathbf{n} \tag{2}$$

where $\mathbf{y} = [r_1(0), \ldots, r_1(T-1), \ldots, r_K(0), \ldots, r_K(T-1)]^T$, is a vector of received measurements stacked together; $\boldsymbol{\beta} = \{\beta_i\}_{i=1}^{I}$ is the pixel values to be estimated and $\mathbf{n}$ is the noise vector assumed to be white with variance σ. The steering matrix $\mathbf{A}$ consists of delayed and scaled versions of the transmitted signal.

The SLIM algorithm estimates $\boldsymbol{\beta}$ and σ via a MAP approach, using a sparsity based *prior*. For accurate estimates, these are solved iteratively, with the values of $\boldsymbol{\beta}$ initialized with the back-projection/DAS algorithm.[20]

3.4 CLEAN

Although the SLIM algorithm improves on resolution and side-lobe reduction, it is computationally intensive, especially when the pixel resolution is high. We also consider a data-dependent CLEAN algorithm[21] (also known as matching pursuit) for image formation. This technique has been used for subsurface imaging in the image domain, producing 'CLEANer' images (where prior knowledge of the point spread function was required).[22] We apply this algorithm in the time-domain (with an estimated transmitted waveform).

This algorithm can eliminate contributions of a single target which can show up at multiple pixel locations due to delay ambiguity. By using multiple transmit and receive pairs, this delay ambiguity can be alleviated. However, if a single target return is very strong, the delay ambiguity can cause such a target to bury returns from much weaker targets during image formation. CLEAN can be used to eliminate the side-lobes of strong returns so that weak targets can be revealed.

We therefore use the CLEAN algorithm to find the pixel location of the strongest target and then subtract all the contributions of that target from the data. The next strongest point is then computed more accurately. The process can be described in the following steps.

- Step 1: Estimate the brightest point $B(i_o)$ and corresponding location (i_o) from the Back-projection image.
- Step 2: Subtract the contribution of brightest point from the received signals.
- Step 3: Generate new image by filling in the (i_o) pixel with $(B(i_0))$.
- Step 4: Use updated received signals to regenerate back-projection image.
- Remaining Steps: Repeat previous steps with regenerated image until predefined threshold.

Both data-dependent methods (CLEAN, and SLIM) require knowledge of the transmitted waveform. The waveform can be estimated from the received measurements based on the following idea.

- Compute the average magnitude spectrum of the received signal over all measurements as an estimate of the spectrum of the transmitted pulse.
- Assume transmitted pulse shape is symmetric about the origin (hence, the transmitted pulse spectrum is real-valued and can be computed from pulse spectrum by an inverse Fourier transform).

Fig. 5 shows a comparison of the proposed data-adaptive (CLEAN and SLIM) algorithms to the data-dependent methods for SIRE imaging using simulated data. Both algorithms provide sparse images, which allows for more accurate detection of targets (mines) from clutter.

Prior to imaging, it is important to note that the received measurements will also contain radio frequency interference which needs to be suppressed. This is due to the band of frequencies which the radar operates (0.3-3 GHz). In the next Section, RFI suppression for this radar's equivalent sampling scheme will be briefly discussed.

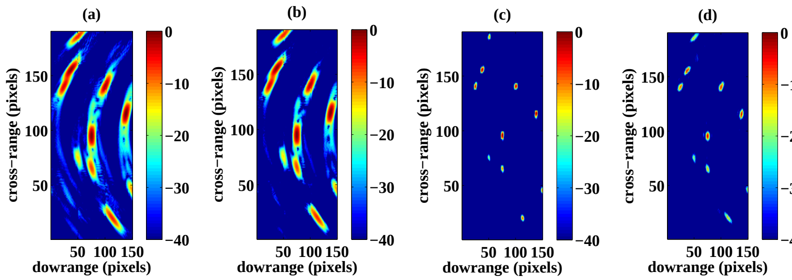


Figure 5. MIMO: Data-adaptive methods compared to data-independent methods: (a) Back-projection (b) RSM (c) CLEAN (d) SLIM.

4. RADIO FREQUENCY INTERFERENCE SUPPRESSION: RELAX AND AVERAGING

Unlike the scene to be imaged which is stationary, the RFI signals also picked up by the SIRE radar are changing with time. This implies that the equivalent sampling will induce aliasing (prior to interleaving) to these signals as well as distort them when interleaved.[16,23] In this Section, suppression of Radio Frequency Interference (RFI) signals based on a relaxation algorithm for this equivalent time-sampling scheme is briefly described.

Conventional suppression schemes such as notch filtering prove to be futile due to aliasing caused by this sampling scheme (A single sinusoid will appear as multiple peaks in the spectrum).[23] An averaging method proposed by ARL which involves averaging repeated measurements from the same range-profile has been shown to suppress both narrowband and wideband interference by a factor of M (M is the number of repeated measurements).[12,16]

This method can be improved by taking into account the structure of the RFI signals which has a much narrower bandwidth relative to target signatures which are ultra-wideband. The aliased samples of the RFI signals can be modelled as a sum of sinusoids in 'real time' (prior to interleaving). Estimating and subtracting the sinusoids in addition to averaging can yield further suppression without signal distortion.[23]

The RELAX[13] algorithm which is a cyclic optimization algorithm is proposed for estimating the parameters of the sinusoids (in an iterative manner). This algorithm is an asymptotic maximum likelihood approach and is computationally and conceptually simple. It has also been shown to estimate the parameters of sinusoids accurately even in the presence of colored noise.[13] The algorithm is briefly described.

The RELAX algorithm estimates the sinusoidal parameters as follows: Let

$$\mathbf{y}_p \triangleq \mathbf{y} - \sum_{i=1, p\neq i}^{P} \hat{\alpha}_i \mathbf{a}(\hat{f}_i) \tag{3}$$

where $\mathbf{y}$ is the data. The frequency and complex amplitude estimates of the pth sinusoid are estimated by $\hat{f}_p = \underset{f_p}{\operatorname{argmax}} |\mathbf{a}^H(f_p)\mathbf{y}_p|^2$ and $\hat{\alpha}_p = \frac{\mathbf{a}^H(f_p)\mathbf{y}_p}{L}|_{f_p=\hat{f}_p}$ respectively . The RELAX algorithm steps are given by:

- Step 1: Assume $P = 1$. Estimate $\hat{f}_1$ and $\hat{\alpha}_1$ from $\mathbf{y}$.
- Step 2: Assume $P = 2$. Compute $\mathbf{y}_2$ based on estimates from the previous step and estimate $\hat{f}_2$ and $\hat{\alpha}_2$. Compute $\mathbf{y}_1$ and re-estimate $\hat{f}_1$ and $\hat{\alpha}_1$. Re-iterate previous steps until practical convergence.
- Remaining Steps: Continue until $P = \hat{P}$, which is an estimated or desired number.

Note that, the frequencies and complex amplitudes are estimated using the DTFT of the signals $\mathbf{y}_p$. This can be efficiently computed using the FFT and zero-padding for conventionally (regularly) sampled data.

The SIRE sampled data is irregularly sampled, hence re-sampling by inserting zeros will allow for an FFT to be used for spectrum computation. This is computationally intensive as the number of frequency grid points is very large. An efficient method of spectrum computation[23] which exploits regular sampling of SIRE data in fast and slow time can be used to speed up the computation.

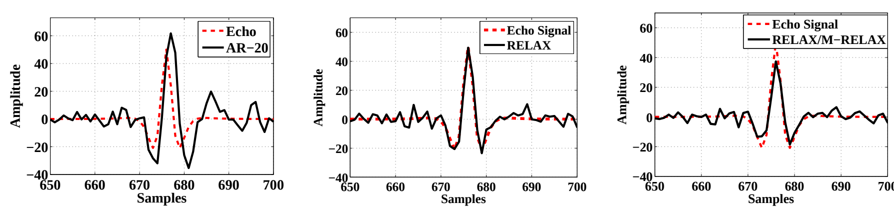
The spectrum is computed by summing up multiple FFTs. Also because the signal is aliased, the spectrum needs only to be computed over a small portion (40 MHz - A/D sampling rate) of the entire bandwidth. This algorithm drastically improves on the computation (a factor of **10** over re-sampling).[23]

This spectrum is used in the RELAX algorithm to estimate the parameters of the sinusoids present. The RELAX algorithm is applied here to one realization ($M = 1$) of SIRE sampled data. Multiple sinusoids are needed to model an interference source with wider bandwidth due to the long acquisition time, the sinusoidal model begins to break down for wideband interferers. The multi-snapshot RELAX[23,24](M-RELAX) algorithm for SIRE sampled data can provide a more accurate sinusoidal model for the RFI signals by using just the fast time samples for estimating the parameters. The number of sinusoids (amplitude, frequency and phase) that can be uniquely identified is therefore limited using the M-RELAX algorithm due to the limited number of samples, hence only $N/3$ sinusoids can uniquely identified.[11]

These algorithms are applied to real data collected using the SIRE radar in passive ("sniff") mode. $M = 88$ realizations of "sniff" data are used for analysis. A simulated echo signal sampled using the SIRE technique and added to each realization. Fig. 6 shows the amount of distortion of the echo signal when Auto-regressive (AR) modelling (applied to slow time samples), RELAX and a combination of RELAX and M-RELAX are applied. Table 1 shows the amount of suppression of the RFI signal (in dB). RELAX leaves the target signatures undistorted, while improving the amount of RFI suppression.[23]

Table 1. RFI Suppression: Suppression in dB

Signal: *"Sniff" (passive data)*				
Averaging	RELAX	M-RELAX	RELAX/M-RELAX ($\tilde{P} = 1$)	AR (order q)
20.89	23.46 ($P = 1$) 28.06 ($P = 10$)	24.19 ($P = 1$)	27.04 ($P = 1$) **31.27** ($P = 10$)	23.21 ($q = 2$) 24.52 ($q = 20$)



(a) AR-20 (b) RELAX ($P = 10$) (c) RELAX/M-RELAX ($P = 10/P = 1$)

Figure 6. Echo signal distortion (P number of sinusoids estimated)

5. CONCLUSIONS

In this paper, we discussed the Synchronous Impulse Reconstruction (SIRE) radar built by ARL for landmine detection. This radar was discussed in a MIMO paradigm as a practical example of a MIMO radar which exploits waveform diversity to provide increased cross range resolution. The downrange resolution of this radar is provided by the wideband signal transmitted. The returns are sampled by low rate A/D converters via an equivalent sampling scheme, making the radar cost effective and practical for actual missions for landmine detection.

Data-independent imaging techniques where reviewed for this radar and data-dependent techniques were proposed for this radar for improved resolution and side-lobe reduction. RFI suppression for this radar's sampling scheme was also discussed, the RFI signals are shown to be suppressed without signal distortion, allowing for more enhanced imaging results.

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